Navigation Challenges for the Orbit Phase of NEAR Shoemaker

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When the NEAR Shoemaker spacecraft began its orbit about the asteroid 433 Eros on February 14, 2000, it marked the beginning of many firsts for deep space navigation. Among these were the design and estimation techniques that were necessary to plan and execute an orbit about an irregularly shaped small body. Knowledge of the mass, gravity distribution, and spin state of Eros had to be quickly improved on final approach in order to predict the effect of trajectory correction maneuvers for capture and orbit control around Eros. This required the use of optical landmark tracking, which used pictures of craters on Eros as landmark information, in addition to the more traditional radio metric tracking from NASA's Deep Space Network. Also, as part of the ongoing effort to improve the Eros physical model, altimeter data from the NEAR laser range instrument was also processed and analyzed. This paper describes the navigation strategy and results for the rendezvous and orbit phases of the NEAR mission. Included are descriptions of the new techniques developed to deal with navigation challenges encountered during the year-long orbit phase. The orbit phase included circular orbits at both 50 km and 35 km radius where the bulk of the science observations were obtained. The low altitude flyovers and landing of NEAR are discussed in a companion paper submitted to this conference.

INTRODUCTION

The Near Earth Asteroid Rendezvous (NEAR) mission was the first to be launched in NASA's Discovery Program. The Johns Hopkins University, Applied Physics Laboratory (JHU-APL) was responsible for designing and building the NEAR Shoemaker spacecraft, and for managing and operating the mission.[1,2] Navigation for the spacecraft was the responsibility of the Jet Propulsion Laboratory (JPL), California Institute of Technology. The goal of this Discovery mission was to determine the physical and geological properties of the near-Earth asteroid 433 Eros and to infer its elemental and mineralogical composition by placing the NEAR Shoemaker spacecraft and its science instruments into close orbit about the asteroid. The spacecraft was renamed NEAR Shoemaker in honor of planetary scientist Eugene Shoemaker (1928 – 1997) in March 2000, after it was in orbit about Eros. Since it was a Discovery class mission, the NEAR project was developed with a minimum of staffing, expense and unnecessary complexity. As a result, the spacecraft had a simple design with fixed-mounted instruments and solar panels, but it included advanced capabilities (especially for ease of pointing) that made it easier to operate by a small flight team.

This paper will present some of the unique features of trajectory design and navigation related to orbiting an asteroid and to designing a robust navigation system for the NEAR mission. The problem of navigating a spacecraft about an asteroid is made difficult by the irregular shape of Eros and by the relative uncertainty, before arrival, in the asteroid physical properties that perturb the spacecraft's orbit. To help solve these problems, the navigation system for NEAR used NASA's Deep Space Network (DSN) radio metric Doppler and range tracking in addition to the new navigation technologies of optical landmark tracking and laser ranging to the asteroid surface. The relative usefulness of each of these data types in the navigation solutions will be shown below. The design of the rendezvous and orbit plan was driven by science requirements and requests. The implementation of the various orbit inclination and size changes depended on the intrinsic stability of the orbits and on the ability of the navigation system to provide accurate orbit estimates. The JPL navigation team was responsible for the orbit design, and the JHU-APL mission design and operations teams implemented the design. Some of the most important orbit design constraints and requirements are discussed below as they relate to the navigation strategy. A complete overview of the rendezvous, orbit phase, and landing for NEAR is presented in Ref. 3, and a detailed description of the design and navigation of the low-altitude flyovers and landing is presented in Ref. 4.

Science Requirements and Goals

Prior to the NEAR Shoemaker rendezvous with Eros, the navigation and science strategy for the orbit phase design was examined in some detail.[5] Each instrument's science team had specific goals that drove the orbit design. For instance, the NEAR Multi-Spectral Imager (MSI) team had requirements to image the surface, both globally and in detail, under various lighting geometries during the orbit phase. This coincided with the navigation requirement to build and maintain a global optical landmark database, which required multiple images of landmark craters taken at different times from different viewing geometries.

The requirements for X-ray/Gamma-Ray Spectrometer (XGRS) observations were to bring the instrument close to the surface (as low as 35 x 35 km orbits) for extended periods of time while also viewing the surface at an oblique solar angle of incidence. This requirement was met by progressively lowering the orbit radius as navigation models were improved so that the viewing geometry could be reliably predicted nearly six weeks in advance. This allowed advance planning and checkout of the instrument pointing sequence. Because of the pointing constraints imposed by the solar arrays and science instruments being fixed to the spacecraft body, the orbit plane was constrained to lie within 20 to 30 degrees of the Eros terminator, and this provided the viewing geometry for XGRS.

The NEAR Laser Rangefinder (NLR) had a requirement to cover the complete asteroid surface with laser range returns at altitudes lower than 100 km. This was accomplished by designing polar orbits with both 50 km and 35 km radius. These low orbits also satisfied the radio science and navigation requirements for determining the gravity field of Eros. Of particular importance to the mission design for rendezvous and orbit phases was the science goal of the NEAR Infrared Spectrograph (NIS) instrument to image Eros at nearly zero phase; i.e., with the Sun directly behind the line of sight of the NIS to the illuminated surface of Eros.

Rendezvous with Asteroid 433 Eros

The original rendezvous with 433 Eros was planned as a sequence of maneuvers scheduled to begin on December 20, 1998. The initial burn was terminated prematurely due to a spacecraft anomaly, and the remainder of the maneuver sequence was not performed. As a result, the spacecraft performed a high-speed flyby within 3900 km of Eros on December 23, 1998. Control of the spacecraft was recovered just prior to this flyby, and images were obtained and processed along with the DSN Doppler and range tracking data to provide initial estimates for some of the physical parameters of Eros.[6] After the aborted maneuvers and the flyby, the mission design team at JHU-APL designed a large maneuver ($\Delta V \cong 932$m/s), executed on 1/3/99, to target a new rendezvous with Eros nearly a year later on February 14, 2000.[7] Although this new trajectory took about a year to return to Eros, it had the advantage of a much slower approach speed of about 20 m/s.

In the months before February 2000, the navigation team was busy testing interfaces with the Mission Operations Team at JHU-APL, planning a new orbit phase, and validating the combined radio metric and optical landmark orbit navigation scenario. In addition, maneuvers were determined to target the Eros orbit insertion maneuver (OIM) at about 300 km from the center of Eros on February 12, 2000. On this date, the orientation of the spin axis of Eros resulted in the north pole region being sunlit and the south pole region in darkness. From *a priori* knowledge of the orientation of the spin axis (good to about 5 degrees), it was known that the Sun would cross Eros' equator in June 2000, so the rendezvous and early orbit were designed to accommodate science observations of the northern polar region. This was the only opportunity to image the northern region during the year-long orbital phase. The lighting conditions can be inferred from Figure 1, which shows the latitude of the Sun during the orbit phase. Since Eros' pole lies nearly in its orbit plane, the seasons of dark and light at either pole persist for several months. The new rendezvous was designed so that the first zero phase fly-over for the NIS instrument occurred for the north polar region just before the OIM.[5] A second zero phase fly-over of the south polar region was planned for October 14, 2000, but it was later cancelled due to failure of the NIS instrument in May 2000.

The OIM was designed to accommodate the uncertainty in both maneuver execution and the mass of Eros. The nominal OIM was chosen so that even in the case of three-sigma execution errors and modeling errors, the initial orbit would not pass excessively close to Eros, and the spacecraft would be captured at Eros. The maneuver parameters affecting the initial orbit were the pointing and magnitude uncertainty.

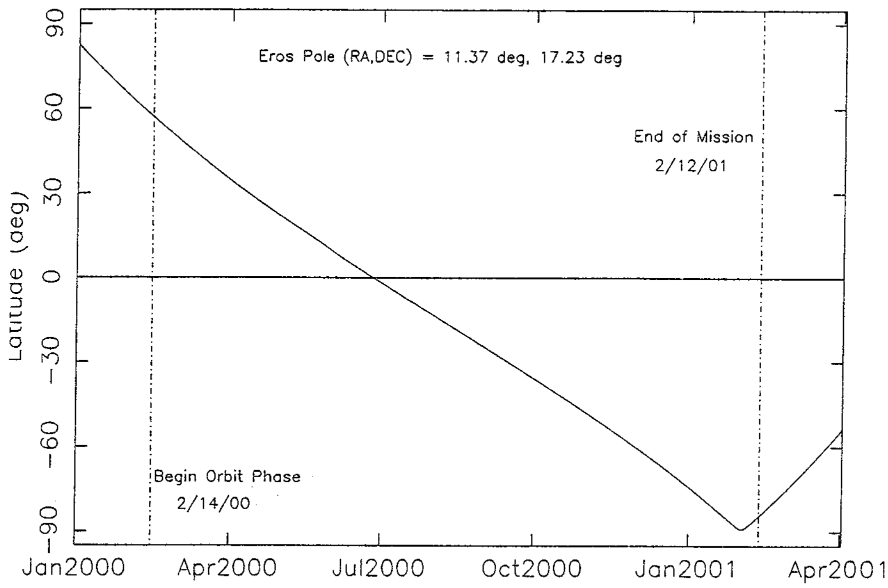

Figure 1. Latitude of the Sun on Eros during the orbit phase.

The radius at the time of the maneuver was uncertain due to prediction errors in the approach trajectory; for the NEAR approach geometry of about 30° to the desired orbit plane, the largest prediction error component (downtrack) affected both the post-OIM orbit radius and orientation.

Prior to the OIM, simulations were performed to determine the range of initial radius of periapsis and apoapsis due to navigation errors. To illustrate the effect for one of these errors, the variation of initial orbit radius for a range of OIM pointing errors is shown in Figure 2. For pointing errors of ±2° along the line to the center of Eros (the worst case direction), the initial orbit remained bounded with minimum periapsis radius of 186 km. For pointing errors of +3 degrees away from Eros and larger, the post-OIM trajectory became hyperbolic. Considering only maneuver magnitude errors of up to ±4 per cent, the resulting initial orbit remained bounded with minimum periapsis radius of 270 km and maximum apoapsis radius of 741 km. Considering only downtrack prediction errors of up to ±100 km, the orbit inclination change was less than the required 30 degrees. Note that the expected range of errors was much less than the values used in these simulations, since the actual maneuver execution errors experienced for this type of maneuver were generally less than one percent in magnitude and less than one degree in pointing. Finally, for variations due to uncertainty in Eros' mass, the post-OIM orbit was perturbed for mass errors of up to ±25 per cent, but the orbit remained bounded with minimum periapsis radius of 310 km and maximum apoapsis radius of 1200 km. After a series of design updates, the post-OIM orbit was targeted two days before the insertion (2/12/00) to a nominal 327 x 452 km; the orbit achieved was 321 x 366 km because the mass of Eros was larger than expected (4.46×10^{-4} km^3/s^2 vs. 4.06×10^{-4} km^3/s^2).

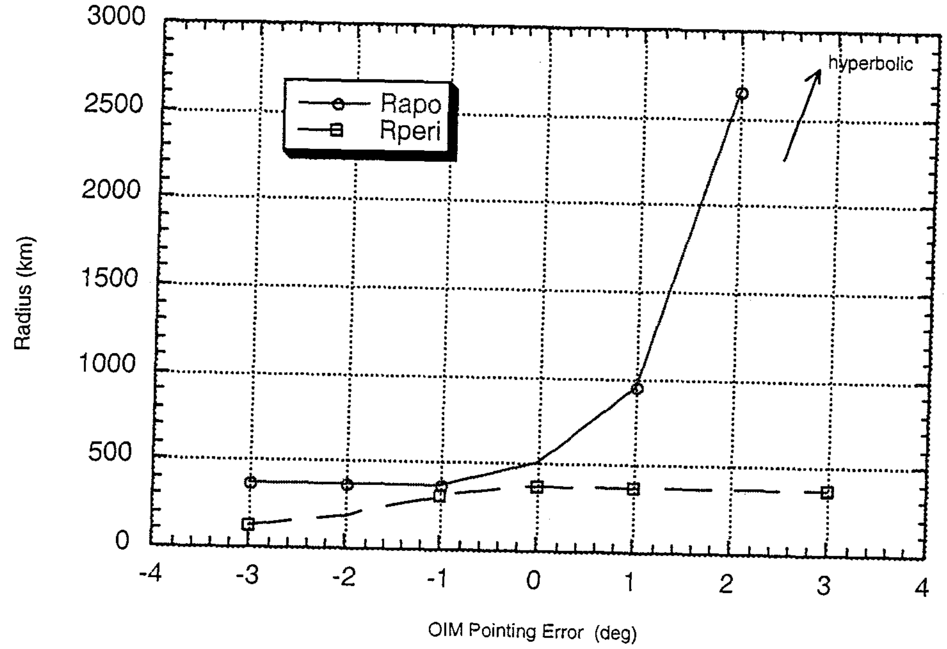

Figure 2. Initial variation of apoapsis and periapsis radius after orbit insertion due to maneuver pointing error.

ORBIT DESIGN

The trajectory design of the orbit phase about Eros departed from that used for previous planetary orbiter missions. For planetary missions, a precise spacecraft ephemeris is designed well in advance of arrival and insertion into orbit. This is possible because the *a priori* knowledge of the planet's mass and size is good enough to predict orbit behavior. In the case of orbits about small bodies, however, the relatively low gravitational attraction means that the orbital velocity is also low. For NEAR Shoemaker the typical orbital velocity in a 50 x 50 km orbit about Eros was about 3 m/s. Small perturbations to orbit velocity could thus lead to either escape or impact with the surface. Also, since the irregular shape of Eros resulted in a non-uniform gravity field, there were concerns of stability for the low orbits; orbit behavior about Eros is analyzed in Ref. 8.

One example of the impact of imprecise knowledge about Eros before arrival was the uncertainty in the orientation of its rotation pole. The pre-arrival estimates of the orientation for the rotation pole of Eros varied by more than 4 degrees. After obtaining the initial landmark tracking during the first few months of the orbit phase, the navigation team was able to estimate the pole orientation to within 0.05 degree, one sigma.[9] This was important not only to orient the gravity field model for subsequent orbit determination and prediction, but it also impacted the mission design by placing a more precise date at which the Sun would cross Eros' equator. As a result of this update, a maneuver originally designed to place the spacecraft into a low polar orbit in July 2000 was moved forward by more than a week.

Similarly, the plan for orbit size and orientation during the year long science gathering phase was periodically revised in response to increased knowledge of the physical parameters and to improved navigation performance as the data taking and processing methods were refined. Because spacecraft pointing was constrained due to the fixed mounted instruments and solar arrays and because the solar arrays had to remain illuminated at less than 30° incidence angle, the orbits were designed to lie within 30° of the "Sun plane-of-sky" (SPOS); i.e., the plane normal to the Sun-Eros line that passes through the center of Eros. A further design constraint established by navigation and mission operations was to place Orbit Correction Maneuvers (OCMs) at least seven days apart, whenever possible. Maneuvers were executed more frequently than this only during the close flyby and landing portions of the orbit phase.

The orbit phase lasted from the insertion burn on February 14, 2000, to the landing on February 12, 2001. A summary of the maneuver times and the resulting orbit geometry is presented in Table 1. In the table, the post-maneuver orbit size and inclination to the Eros true equator are indicated. The initial orbit inclination, even though it resulted in direct orbits, was chosen to reduce the number of burns needed (to save fuel) and to expedite the transition to lower orbits (before the Sun set in the northern hemisphere). The orbit radius for these lower inclination, direct orbits was large enough to avoid excessive instability, and by the time the lower orbits were reached in April, the inclination was polar so the orbits were stable. Note that targeting details resulted in orbits slightly different from the idealized circular orbits; i.e., the first '50 x 50 km' orbits established on April 30, 2000, were actually closer to 49 x 52 km. Also indicated in Table 1 is the approximate time spent in each orbit. The thirty day period in the large 203 x 206 km orbit was used for global mapping and for initial tuning of navigation models for Eros. The navigation strategy that allowed orbit and physical parameter estimates to stabilize at a higher altitude before proceeding to the next lower orbit radius is evident in the early part of the table. The improvement in navigation accuracy as the models were refined and the orbit radius was lowered is discussed in a later section.

Figure 3 shows the NEAR trajectory for the entire orbit phase projected into the SPOS with the origin at the center of mass of Eros. The top view, looking normal to the Sun-Eros line, illustrates the 30° orbit inclination constraint mentioned above. The end of mission descent to landing is shown to scale as the crooked line near the origin in the lower view in Fig. 3. The orbit radius and inclination relative to the Eros equator were varied throughout the orbit phase to accommodate various science instrument observations at low altitude. Specifically, NEAR spent about 76 days in a 50 x 50 km polar orbit, about 10 days in a 35 x 35 km polar orbit, and about 58 days in a 35 x 35 km equatorial (retrograde) orbit. Direct orbits at these lower altitudes were avoided since they were found generally to be unstable. The elongated shape of Eros, with maximum radius of about 18 km, resulted in frequent passes at altitudes less than 17 km in the 35 x 35 km orbits. There were also several transition orbits up to 200 x 200 km where global observations were obtained.

Table 1. Summary of Eros Orbit Phase

Date	Maneuver†	DOY	Orbit (km x km)	Period (Days)	Inc. (deg.) ATE*	Approx Length (Days)	ΔV (m/s)
Feb. 14, 2000	OIM	45	321 x 366	21.8	35	10	10.00
Feb. 24, 2000	OCM-1	55	204 x 365	16.5	34	8	0.13
Mar. 3, 2000	OCM-2	63	203 x 206	10.1	37	30	0.22
Apr. 2, 2000	OCM-3	93	100 x 209	6.7	55	9	0.50
Apr. 11, 2000	OCM-4	102	99 x 101	3.5	59	11	0.37
Apr. 22, 2000	OCM-5	113	50 x 101	2.2	64	8	0.45
Apr. 30, 2000	OCM-6	121	49 x 52	1.2	90	68	1.92
July 7, 2000	OCM-7	189	35 x 51	1.0	90	7	0.32
July 14, 2000	OCM-8	196	35 x 39	0.8	90	10	0.24
July 24, 2000	OCM-9	206	36 x 56	1.1	90	7	0.34
July 31, 2000	OCM-10	213	49 x 52	1.2	90	8	0.50
Aug. 8, 2000	OCM-11	221	50 x 52	1.2	105	18	1.01
Aug. 26, 2000	OCM-12	239	49 x 102	2.3	113	10	1.40
Sept. 5, 2000	OCM-13	249	100 x 103	3.5	115	38	0.96
Oct. 13, 2000	OCM-14	287	50 x 98	2.2	130	7	1.31
Oct. 20, 2000	OCM-15	294	50 x 52	1.2	133	5	0.58
Oct. 25, 2000	OCM-16	299	19 x 51	0.7	133	0.8	0.76
Oct. 26, 2000	OCM-17	300	64 x 203	5.4	145	8	1.66
Nov. 3, 2000	OCM-18	308	194 x 196	9.4	147	34	0.54
Dec. 7, 2000	OCM-19	342	34 x 193	4.2	179	6	0.96
Dec. 13, 2000	OCM-20	348	34 x 38	0.8	179	43	1.23
Jan. 24, 2001	OCM-21	24	22 x 35	0.6	179	4	0.54
Jan. 28, 2001	OCM-22	28	19 x 37	0.6	179	0.7	0.56
Jan. 28, 2001	OCM-23	28	35 x 36	0.8	179	5	0.68
Feb. 2, 2001	OCM-24	33	36 x 36	0.8	179	4	0.02
Feb. 6, 2001	OCM-25	37	36 x 36	0.8	179	6	0.01
Feb. 12, 2001	De-Orbit	43	—	—	135	—	2.54

* ATE – Asteroid True Equator

Approximate Total ΔV = 29.8 m/s

† OIM – Orbit Insertion Maneuver; OCM – Orbit Correction Maneuver

Improving Physical Models

The placement of optical navigation pictures and OCMs was iterated among the mission design, science, navigation, and spacecraft engineering teams to operate within constraints throughout the orbit phase. The overall shape and size of Eros had to be determined early during the orbit phase to enable the close in orbits desired by the MSI, NLR and XGRS instruments. By using both landmark locations and the NLR data, the irregular shape of Eros was determined; the principal radii were measured to be about 16.5, 8.0, and 6.5 km.[10] The orientation of Eros' spin axis was important for timing orbit plane change events as mentioned previously, but the spin orientation and rate also

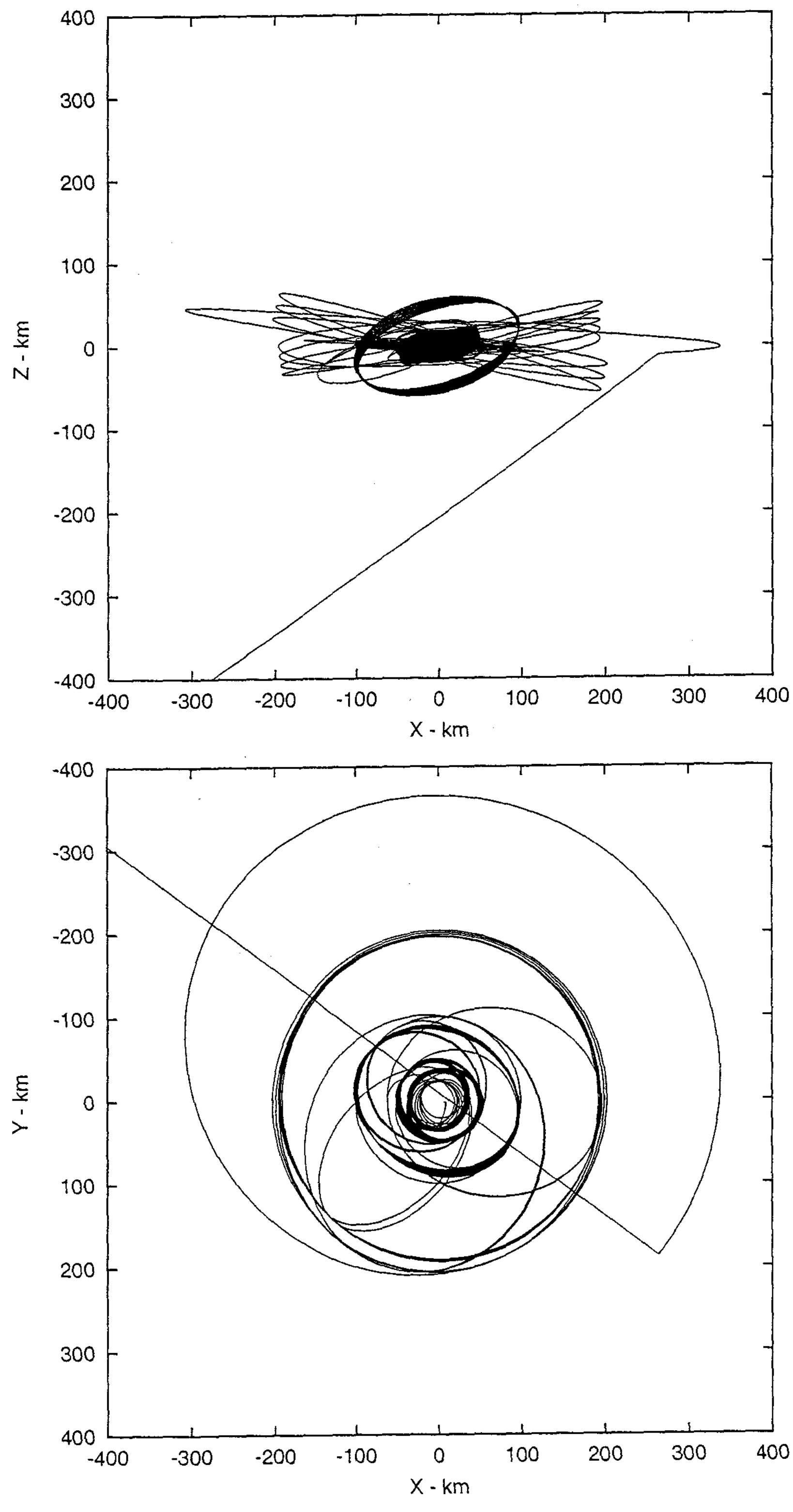

Figure 3. Approach (diagonal line) and orbit phase of NEAR covering February 14, 2000 to February 12, 2001, shown (bottom) in the plane normal to the Sun-Eros line (the Sun plane-of-sky), and (top) in an orthogonal top view. The origin is at the center of mass of the asteroid 433 Eros.

oriented the gravity field model which was critical for subsequent orbit determination and orbit prediction. After additional data were processed, Eros' rotation pole right ascension was estimated to be 11.369 ±0.003 deg, one sigma, and pole declination was 17.227 ±0.006 deg, one sigma in J2000 coordinates.[11] Similar updates to physical models (especially the Eros gravity model) and improvements in navigation accuracy resulted in the orbit phase being re-planned by the navigation team a total of seven times after orbit insertion. The end-of-mission close flybys scheduled after January 24, 2001 were re-planned a total 3 times in response to improvements in orbit prediction accuracy.

End of Mission Plan

After the main science goals of the mission had been met and the navigation models and experience had been tuned by eleven months of orbiting Eros, another series of low-altitude fly overs was planned for late January 2001. This came at the end of a long interval of 35 x 35 km retrograde equatorial orbits that began on December 13, 2000. These low orbits were designed to meet XGRS viewing requirements. The approach this time was to establish an eccentric orbit measuring 35 x 22 km on January 24, remain in that orbit for several days, stabilize the orbit determination estimates and trajectory predictions, and then lower periapsis further on January 28, 2001 (OCM-22), to 37 x 19 km so that a target altitude between 2 and 3 km was achieved. The OCM-22 maneuver resulted in the closest over flight of about 2.7 km on January 28, 10:24 UTC, and was followed about 16 hours later by OCM-23 which returned to the 35 x 35 km circular orbit.

Navigation plans for the end of NEAR Shoemaker's mission were reviewed by the Science and Mission Operations teams. The end-of-mission phase began on January 10, 2001, and ended on February 14, 2001. The science team requested the following additional orbit conditions be included in the last weeks of the mission: (1) at least 10 high-inclination orbits at less than 35-km radius; (2) at least two low-altitude (2-5 km) flyovers at scientifically interesting sites, with the minimum altitude chosen to minimize risk (i.e., it depended on latest navigation error estimates); (3) imaging at two or more sites with resolutions of about 10 cm or better, requiring altitudes of roughly 500 meters; and (4) magnetometer measurements in the wake region (i.e., Eros' shadow region). The Mission Operations Team concluded that a passage through Eros' shadow region would involve unacceptable risk (battery required for power), and might end the mission prematurely, so the orbit design was constrained to avoid solar occultation. The other requests were met with the exception that only one site was imaged at 10-cm resolution (the landing site) because there was not enough fuel to consider a second site. This paper will not discuss the details of the close flyovers and landing of NEAR, as that topic is covered Ref. 4.

ORBIT ESTIMATION

Orbit determination (OD) techniques for the orbital phase of NEAR were developed prior to launch.[12] Through simulations and covariance analyses, it was determined that the OD filter design and operations for Eros would have to be different from that used for previous planetary orbiters. The two main changes in strategy were (1) the need to simultaneously estimate the spacecraft orbit, non-gravitational accelerations, and Eros' physical parameters related to the spacecraft orbit dynamics, and (2) the need to augment the DSN Doppler and range tracking with optical landmark tracking. In addition, the

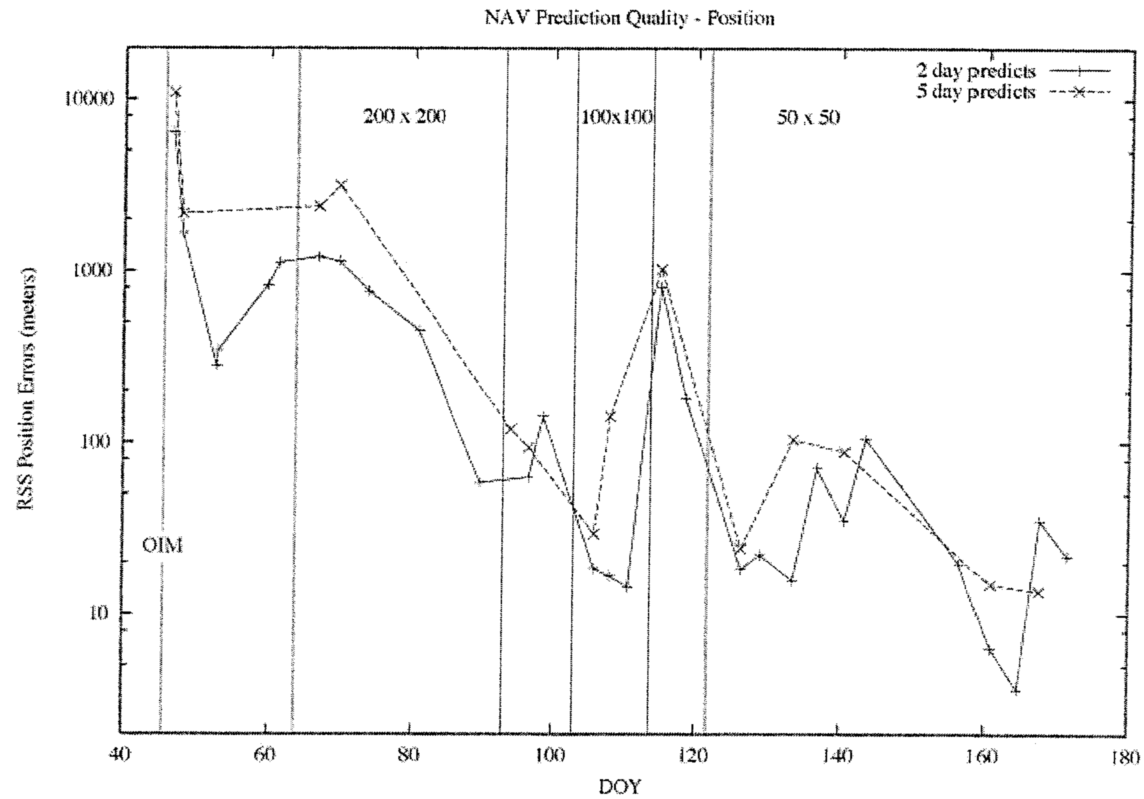

Figure 5. Orbit determination position prediction performance for the first few months of the orbit phase.

utility of the laser range data as an auxiliary tracking data type was established. The OD performance prediction was validated during orbit operations, and even though the actual orbit scenario changed due to the later insertion date, the technique of progressively improving model resolution and reducing the orbit radius performed as predicted by the analysis in Ref. 12.

The OD performance during the early orbit phase, when the model improvement was most dramatic, is shown in Figure 5. The figure shows the root-sum-square (RSS) position error for both 2 day and 5 day long predictions as compared to orbit reconstructions using the final improved models. The vertical lines in the figure denote times of OCMs, and the intervals of nominal circular orbit phases of 200 x 200 km, 100 x 100 km, and 50 x 50 km are labeled between the appropriate maneuver lines. Notice that the vertical scale is logarithmic, labeled from 10 meters to 10 km. The initial improvement after OIM to the 100 km circular orbits reduces the prediction error from over 1 km to less than 100 m. The dramatic change after going to the 100 x 50 km transfer orbit at about day of year (DOY) 115 shows the sensitivity of prediction at the lower orbit to Eros model errors that have not yet been improved. Also, position errors are affected when the orbit is predicted from an orbit fit that includes an OCM. The long time in the 50 x 50 mapping orbit allowed some further experimentation on estimated parameters and filter setup that led to further improvements so that the average prediction error by the end of the plot in Figure 5 is 10 to 20 m or less. Note that the OD knowledge within the fit arc at the end of this period amounted to only a meter or two in position.

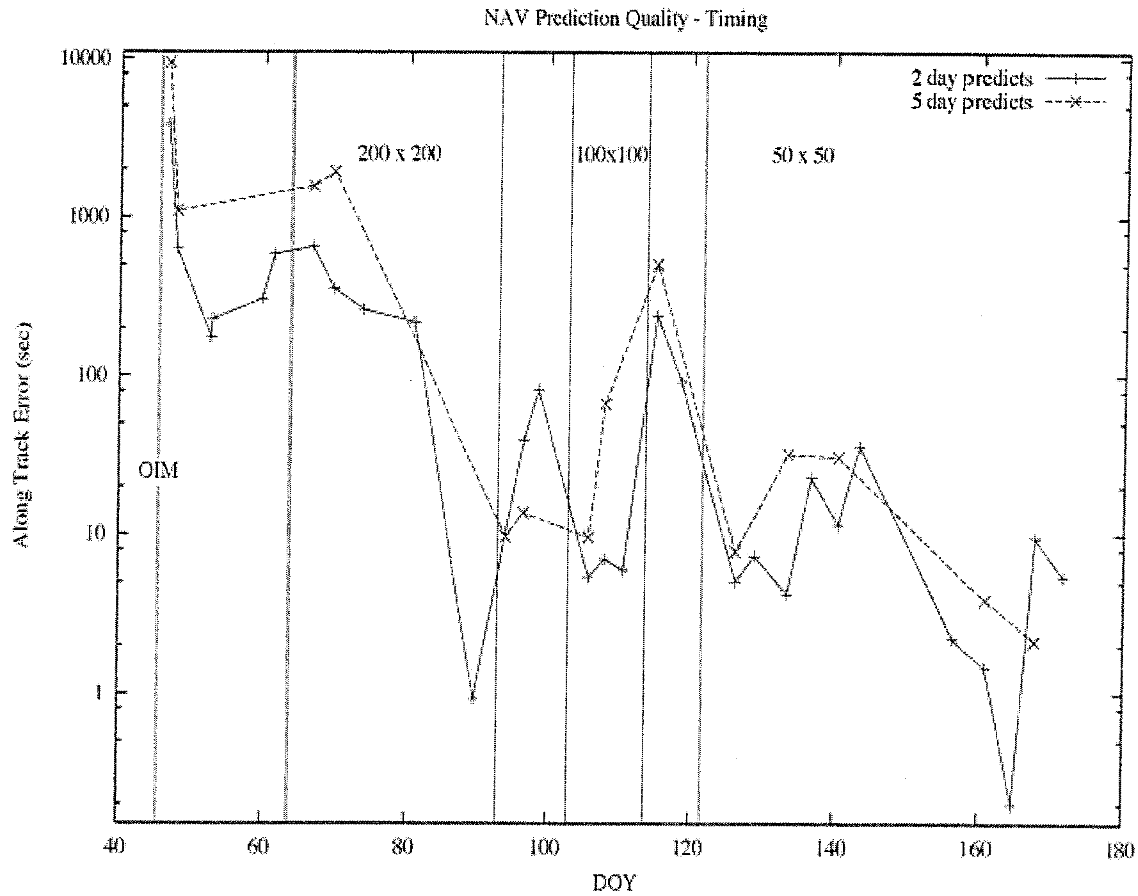

Figure 6. Orbit determination along track prediction performance for the first few months of the orbit phase.

The error in predicted orbit timing was especially important for the sequence planning process used for NEAR operations. This process used navigation predictions of OCM execution times and the resulting orbital shape and orientation to plan sequences up to four weeks in advance.[13] For MSI advanced planning, the predictions were extended to as much as eight weeks in advance. The orbit timing errors for the same early orbit period covered by Figure 5 are shown in Figure 6. The timing error is proportional to the downtrack position error for each prediction. Note that early in the orbit phase, it was difficult to predict the time of upcoming maneuvers to better than several minutes even for the short prediction times shown in Figure 6. It was even more difficult to predict the times of later burns in a multi-burn sequence design, since the orbit determination was degraded by having to solve for several maneuvers in the fit. This effect is seen in Figure 6 where the timing error rises after a burn even for the short prediction times. The impact of this behavior was the need to provide trajectory predictions for both preliminary planning of an OCM about a week in advance and a trajectory prediction for a final update of an OCM about two days in advance. This meant that the navigation team usually generated two orbit prediction deliveries per week except during intervals where OCMs were more than three weeks apart.

Radio Metric Tracking

DSN radio metric data was one of the data types used for navigation of NEAR. The radio metric data types available included (1) 2-way X-band Doppler and range, (2) 2-way minus 3-way Doppler (Narrow band VLBI), and (3) 1-way X-band Doppler (not processed). The 2-way Doppler was weighted at 0.1 mm/s for 60 s count time, and the 2-way range was weighted at 200 m. The range was de-weighted during the orbit phase since it primarily contained information for adjusting Eros' ephemeris, while the Doppler was much more useful for determining the spacecraft orbit relative to Eros. The routine processing used only the 2-way Doppler and range. During approach and rendezvous, a combination of 2-way Doppler and range plus available 2-way minus 3-way narrow band VLBI (differenced Doppler from DSN station overlap coverage) was used as a consistency check. When processed in the orbit determination filter, the DSN inter-complex timing offset between the two antennas (measured to a few nanoseconds) was used to calibrate the differenced Doppler points.

After the initial model tuning phase indicated in Figures 5 and 6, the Doppler data taken during a 60 day arc in the 50 x 50 km orbit were fit to about 0.05 mm/s, rms. The range data, being de-weighted in the OD filter, had systematic trends in the post-fit residuals as large as several hundred meters; however, the range data were only used to loosely control the Eros ephemeris estimate, and did not affect the spacecraft orbit estimate relative to Eros for the short arcs (relative to Eros' orbit period) used in production. Later processing of long arcs of range data weighted at 10 m, which is a more realistic precision, was used to improve the overall estimate of Eros ephemeris.[11]

Optical Landmark Tracking

The optical landmark tracking process for NEAR had two characteristics. One was the initial identification and determination of a set of landmark craters (the landmark database), and the other was finding and using those same landmarks in subsequent pictures as tracking data. These two functions overlapped since the initial optical navigation task in orbit was to refine the location estimate of landmarks while also building up the landmark database. Hence, the picture planning process had to provide enough pictures to build a reasonable number and distribution of landmarks, and it had to provide designated optical tracking images of previously identified landmarks. Before the landmark locations are precisely known, the tracking information from optical landmark images is in measuring the apparent motion of a landmark in a series of pictures where viewing geometry is changing due to the relative motion of Eros spinning about its axis and the orbit of the spacecraft. By processing many such landmark images in the orbit determination filter, both orbit and landmark locations can be estimated. Once calibrated, the optical landmarks obtained during a 60 day arc in the 50 x 50 km orbit were fit to about 15 m, rms. Note that a single picture of a landmark is useless as navigation tracking data.

Building and maintaining the landmark database was an ongoing process throughout most of the orbit phase because of the unique lighting conditions at 433 Eros. Upon arrival, only the north polar region of Eros was in sunlight. During the first few critical months of the orbital phase, there were optical landmarks only in that lit hemisphere. As Eros moved in its orbit about the Sun, the southern hemisphere was eventually lighted, and landmarks from that hemisphere were added to the database. Table 2 presents a summary of some characteristics of the optical landmark process for NEAR. The details of optical landmark processing and results are given in Ref. 14.

Table 2. Operational summary of optical landmark tracking for NEAR over the entire approach and orbit phase.

Optical Landmark Processing Characteristic	Quantity	Percent of Total
Total number of pictures taken starting 12/17/1999	181,393	
Number of pictures downloaded to JPL for analysis	33,968	(18.73%)
Number of useful pictures (at least 1 landmark)	17,601	
Number of accepted pictures (some incorrect attitude)	17,352	
Number of star calibration pictures	1,424	
Number of valid landmarks in database	1,590	
Number of landmark observations	134,267	
Number of misidentified landmark observations	1,314	(0.98%)
Number of landmark observations in pictures with incorrect attitude	1,616	(1.20%)
Number of useful landmark observations	131,337	(97.82%)
Average number of useful observations per landmark	82.6	
Average number of useful observations per picture	7.6	

Laser Range Tracking

The NEAR Laser Rangefinder (NLR) instrument provided useful altimeter range measurements to the surface of Eros whenever the range was less than a couple of hundred kilometers. This information was used to assist navigation in two ways. The first method was to use the NLR data in the orbit determination filter, either alone or in combination with other tracking data, to solve for the spacecraft orbit. The second method was to use the NLR data to solve for an accurate shape model of Eros which was then used to determine an *a priori* gravity harmonic model for Eros (assuming uniform density). In addition, an accurate shape model also was a benefit to the optical landmark processing, both by providing a convenient way to catalog the landmarks on the surface and by providing better *a priori* locations for landmarks with a small sample size.

The direct use of NLR data for orbit determination was never used for NEAR navigation operational deliveries, but the technique was used as a consistency check on the production orbits that were produced by processing DSN radio metric Doppler and range combined with optical landmarks. The navigation performance when using NLR data either alone or in combination with the radio metric and optical landmark tracking is described in Ref. 10. By holding the orbits computed with radio metric and optical data fixed, the altimeter range data was successfully used to estimate an Eros shape model,

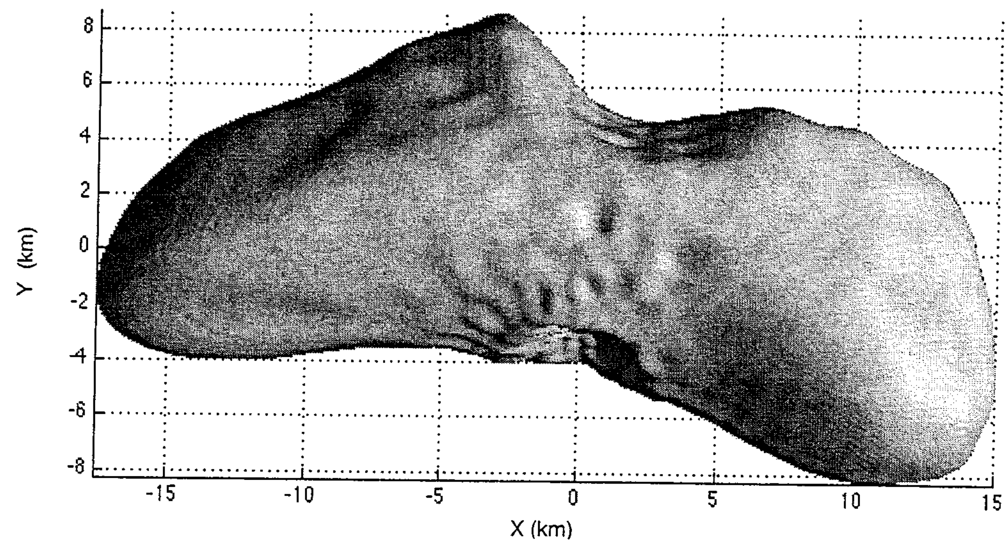

Figure 7. Spherical harmonic 34th degree and order shape model for Eros derived from laser ranging. South pole is shown at origin.

which is shown in Figure 7. The shape model was determined by solving for a 34th degree and order spherical harmonic expansion of Eros' radius. Note the figure shows some possible aliasing around the minimum radius 'belt', but there is also good resolution of some of the larger craters there. Tests show the navigation shape model is probably good to about 50 m, rms. The poorest determined shape areas are in the concave region near the lower center in Figure 7 (where the large crater can be seen) and toward the two long radius 'ends'. In these poor regions, the shape is only good to about 100 m, rms. It is surprising that even this level of fit can be obtained considering the non-spherical shape of Eros. Furthermore, during this process estimates for the NLR pointing error, range bias, and altitude degradation factor were obtained. The value for this pointing error is close to the independently observed pointing error for the camera, making the estimate more credible. The shape model also agrees at the 100 m level with the landmark heights, which are determined through the optical tracking data. The landmarks are consistently biased above the shape model, which is reasonable since the landmark point is idealized as the center of the circle defined by the crater rim.

The orbits computed with the combined NLR data and radio metric data agree with the operational orbits at about the 40 to 50 m level. Even after estimating a pointing error, range bias, and degradation factor, the NLR data seems to bias the orbits at this level, especially in the transverse direction. The complete cause and fix for this biasing have yet to be determined. Likely causes of this could be time tag errors, instrument performance problems, or additional pointing errors that are not accounted for.

SUMMARY

The NEAR Shoemaker spacecraft was the first to orbit a small body. The design and estimation techniques necessary to plan and navigate its orbit about an irregularly shaped small body had to be developed and tested as the mission progressed. Knowledge of the mass, gravity distribution, and spin state of Eros had to be quickly improved on final approach and during the orbit phase in order to predict the effect of trajectory correction maneuvers for capture and orbit control around Eros. The navigation challenge for the orbit phase was to adapt the orbit plan while adjusting for the crudely known asteroid physical parameters. Improvements in the estimates of Eros' physical parameters as the spacecraft approached and inserted into orbit about the asteroid were crucial to mission success. Unlike a planetary orbiter, the very low gravity of Eros ($\mu = 4.46 \times 10^{-4}$ km^3/s^2, Ref. 11) meant that the spacecraft could easily escape or crash into the surface of Eros with small changes in velocity. This placed additional demands on navigation accuracy while also imposing a generally shorter response time than that usual for planetary orbit missions.

The weak, non-spherical gravity field around Eros, combined with solar pressure accelerations, resulted in the low altitude NEAR orbits being highly perturbed, non-Keplerian, and difficult to predict. To estimate these orbits, the gravity field and its orientation in space also had to be estimated, and when using only radio metric data these estimates were slow to converge. This required the use of optical landmark tracking, which used pictures of craters on Eros as landmark information, in addition to the more traditional radio metric tracking from NASA's Deep Space Network. The operational use of optical landmark tracking for a deep space mission was another navigation first for the NEAR mission.

The NEAR mission posed several new and difficult challenges for spacecraft navigation. Many of these resulted from the fact that NEAR was the first mission to send a spacecraft to rendezvous with, orbit about, and finally land on an asteroid, the asteroid 433 Eros. The navigation team responded by developing new tracking data types and new processing methods specifically for NEAR navigation. Many of these techniques should prove useful for navigation of future missions to asteroids and comets.

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